A Computer Simulation of the Effect of Fading on a Quasi-Synchronous Sideband Diversity AM Mobile Radio Scheme

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Abstract—In this contribution, a software multipath fading simulation package (previously applied to the statistical analysis of the fading statistics of single transmitter schemes for three very different mobile radio environments) is used to analyze the performance of a quasi-synchronous, multitransmitter, amplitude modulated sideband diversity area coverage system. By conducting field trials in an area known to obey Rayleigh fading statistics, it has been possible to compare the simulated statistical results to those obtained theoretically and experimentally, and to show that good agreement exists. The fading simulator is capable of being extended to other types of multitransmitter radio scheme employing different forms of modulation.

I. Introduction

THE civil land mobile radio service provides some of the worst conditions for the propagation of radio signals. This situation exists since there is seldom a line-of-sight signal between transmitter and receiver so that, consequently, any signal received must be a composite of scattered and reflected waves. The interaction of these waves arriving at the antenna of the mobile can cause random fluctuations in the received signal level of up to 35 dB, several times per second at VHF. In the UHF frequency band the situation is even worse in that a mobile receiver operating at a frequency of 460 MHz and traveling at 112 km/h will experience similar fluctuations in received signal level but at rates up to 95 times/s. These random fluctuations, commonly referred to as fast or multipath fading, can seriously impair the intelligibility of speech in an amplitude modulated (AM) or frequency modulated (FM) channel and cause an unacceptable error rate for data communications.

To comprehensively test a particular modulation system in the field is uneconomic in terms of both time and manpower. Yet, to design radio schemes which reduce the effects of fading, it is essential to statistically analyze the process and to be able to predict the result of changes in the system parameters or environment. As a consequence, many simulations of multipath propagation have been developed [1], [2] in an attempt to fully investigate modulation schemes under controlled laboratory conditions. The majority of these simulations have been approached from the hardware standpoint and, as such, are inclined to be inflexible and produce fading which follows the theoretical Rayleigh statistics. However, this has been shown by several researchers [3], [4] to be an inadequate representation and for this reason the authors have developed a computer simulation of multipath fading in the land mobile environment [5] which takes into account vehicle movement, shadowing, and direct component signals. As fading is inherently a random process, it is well suited to numerical techniques and, thus, to computer simulation.

In this previous work, the simulation model was used to successfully predict the fading statistics of a single transmitter scheme for three very different types of mobile radio environment in the City of Bath. Unlike other simulators, this particular software approach proved extremely versatile in being able to accurately predict the statistics of areas with Rayleigh and non-Rayleigh characteristics besides those with Rician statistics. In this paper, it is intended to describe the application of the simulation package to the design of more complex radio systems, a necessary step in establishing the credibility of the package as a possible computer-aided design tool for radio-communication engineers. For this reason, it is intended here to apply the simulation to the analysis of the fading statistics in multitransmitter synchronous and quasi-synchronous, full carrier AM sideband diversity schemes [6]–[8]. Although this area coverage scheme is somewhat specialized and limited to the U.K. for the present, it clearly represents an extremely stringent test for the fading simulator but one which, nonetheless, must be satisfied. Although the theory of sideband diversity will be discussed in a little more detail later in the paper, it is pertinent to describe the basic principle of the technique here.

In recent years, many forms of diversity technique have been described for reducing the effect of multipath fading on the output signal from the receiver [9]–[11]. The sideband diversity scheme uses two or more transmitters, spa-

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tially separated, with their carrier frequencies, in quasi-synchronous form, offset by a small amount. In its simplest form the carriers are amplitude modulated, the modulation having a constant phase difference between each of the transmitters. The basic operation of the system can be demonstrated by considering a two-transmitter scheme with a carrier offset of $\Delta\omega$ and an audio phase shift of α such that the transmitted signals are

$$E_1(t) = A_1\left(1 + m\cos\left(\omega_m t + \frac{\alpha}{2}\right)\right)\cos\left(\left(\omega + \frac{\Delta\omega}{2}\right)t\right) \quad (1)$$

and

$$E_2(t) = A_2\left(1 + m\cos\left(\omega_m t - \frac{\alpha}{2}\right)\right)\cos\left(\left(\omega - \frac{\Delta\omega}{2}\right)t\right). \quad (2)$$

At a point in the area of overlap for the two transmitters, where the amplitudes of the two signals are equal, i.e., $A_1 = A_2$, the received sidebands will be

$$E_s(t) = Am\left(\cos\left(\omega_m t + \frac{\alpha}{2}\right)\cos\left(\left(\omega + \frac{\Delta\omega}{2}\right)t\right) + \cos\left(\omega_m t - \frac{\alpha}{2}\right)\cos\left(\left(\omega - \frac{\Delta\omega}{2}\right)t\right)\right) \quad (3)$$

which may be expressed as

$$E_s(t) = \frac{Am}{2}\left(\cos\left(\frac{\Delta\omega t + \alpha}{2}\right)\cos\left((\omega + \omega_m)t\right) + \cos\left(\frac{\Delta\omega t - \alpha}{2}\right)\cos\left((\omega - \omega_m)t\right)\right). \quad (4)$$

The first factor of each term represents the interference of the two signals causing each sideband to fade regularly. If the audio phase shift is set to $\pi/2$, it can be shown that one sideband will be at a maximum while the other goes through a null. By demodulating the sidebands independently and selecting the larger one to provide the final output signal, the undesirable effects of the interference can be overcome. This basic analysis can be extended to the field situation where both signals undergo multipath fading. If the fading of the signals is uncorrelated (through the spatial separation of the transmitters), then the fading of the sidebands approaches negative correlation. By using the selection technique, the overall effect of multipath propagation can be significantly reduced. However, the type of analysis does not provide a true reflection of what happens in a practical scheme where system parameters can be far from ideal, e.g., regions where the mean signal levels are not equal or where the fading is partially correlated.

The paper begins with a description of the multipath fading simulator and the theory of sideband diversity in Rayleigh fading before applying the simulator to predict the envelope fading statistics of Great Pulteney Street in the City of Bath for both synchronous and quasi-synchronous sideband diversity schemes. Great Pulteney Street was chosen since it was the only roadway investigated which possessed Rayleigh fading statistics, thereby allowing theoretically predicted results to be *directly compared* with those from the simulation and those obtained from an experimental, short baseline, quasi-synchronous sideband diversity scheme.

II. Basic Description of Simulation Model

A. Theory of Multipath Fading

As a mobile moves through an urban or suburban area, it receives a large number of radio waves reflected from the surrounding buildings and objects. Clarke [12] suggested that these waves could be assumed to have equal magnitudes and uniformly random phase shifts, and to arrive at the receiver aerial from all directions with equal probability. Each wave would have a Doppler shift ω_n, related to the angle of arrival α_n by

$$\omega_n = \frac{2\pi f v}{c}\cos\alpha_n \quad (5)$$

where f is the carrier frequency, c is the velocity of light, and v is the velocity of the vehicle. Following the work of Rice [13], the resultant electric field would be the complex sum of individual waves and can be expressed as

$$E(t) = T_c(t)\cos(\omega_c t) - T_s(t)\sin(\omega_c t) \quad (6)$$

where

$$T_c(t) = E_0 \sum_{n=1}^{N} C_n \cos(\omega_n t + \theta_n) \quad (7)$$

and

$$T_s(t) = E_0 \sum_{n=1}^{N} C_n \sin(\omega_n t + \theta_n) \quad (8)$$

in which C_n and θ_n denote the amplitudes and phase shifts of each wave and ω_c is the angular carrier frequency. Since the phases θ_n and the arrival angles α_n are both assumed to have uniform distributions, and the amplitudes C_n are either all equal or are Gaussian variables, the quadrature components $T_s(t)$ and $T_c(t)$ tend, by the central limit theorem, to Gaussian processes as the number of waves N becomes large. The magnitude of the received signal level $r(t)$ is equal to the magnitude of the electric field strength:

$$r(t) = |E(t)| = \left\{T_c^2(t) + T_s^2(t)\right\}^{1/2} \quad (9)$$

and tends by definition to follow the Rayleigh probability density function. The Rayleigh distribution function is well defined, and has the general form

$$p(r) = \frac{r}{\sigma^2}\exp\left(\frac{-r^2}{2\sigma^2}\right) \qquad \text{for } r > 0 \quad (10)$$

in which σ^2 represents the mean power level. The corresponding cumulative distribution function is given by

$$P(r < R) = \int_{-\infty}^{R} p(r)\,dr = 1 - \exp\left(\frac{-R^2}{2\sigma^2}\right). \quad (11)$$

Gilbert [14] has shown that, even when as few as three waves are used, the signal level approaches the Rayleigh function, although it is more usual to define a model with at least six independent waves. When the amplitude of the signal envelope does follow this function, it is commonly referred to as "Rayleigh fading." It has, however, been noted by several workers [3], [4] that the secondary statistics, such as power spectral density, level crossing rate, and mean duration of fade, often deviate from those suggested by this model even when the cumulative distribution function closely agrees with the theoretical curve. When the signal received at the mobile includes a coherent or line-of-sight wave, the resulting statistics no longer obey the Rayleigh fading model. The statistics for this case have been evaluated by several workers [15], [16], although the original work is due to Rice [17], from whom the distribution takes its name.

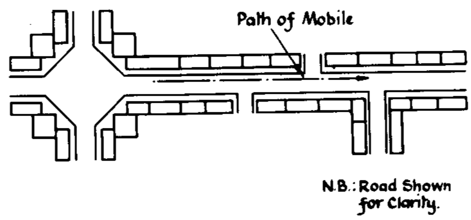


Fig. 1. Simulation plan.

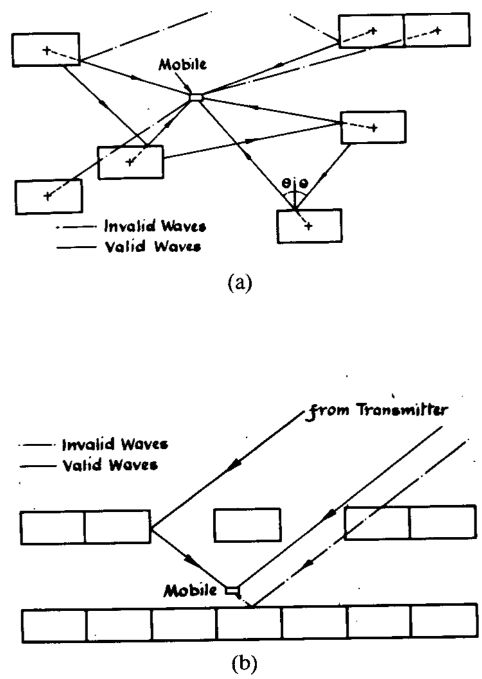


Fig. 2. (a) Simulation rules. (b) Coherent waves.

B. Digital Simulation

1) Area Plan: The central section of this particular computer simulation, and its starting point, is a plan of the area under consideration, e.g., as in Fig. 1. Although the plan is now very similar to a map, it should be noted that it is still a statistical representation. The sides of the rectangles define the edges of the buildings in the area and are treated as plane reflectors. Building centers are regarded as acting as point scatterers. A mobile traveling along the road receives waves from each scatterer, either directly or by single reflection, as shown in Fig. 2. The direct, or primary, waves can only pass through the block from which they originate, thus allowing each of the rectangular areas to act as a possible source of shadowing for the signal. By reason of this inherent shadowing, waves from distant scatterers are restricted. In particular, this is true for plans on which the rectangular blocks are sited along each side of the road, such that, if a wave makes a small angle to the mobile's direction of travel, then, in all probability, it will be obstructed by the corner of an adjacent block, as in Fig. 2. The ability to incorporate some degree of shadowing is one of the novel features of this particular simulation and is close to what actually happens in the field. The arrangement of the rectangles on the plan, although representing a physical environment, does not require that each building should be included as a separate block. The grouping is organized on a statistical basis, e.g., a terrace would be broken up into equal-sized blocks. Although there is need for further work into the sizes of blocks represented on the plan, our work to date has shown that the results obtained are not overly sensitive to their dimensions.

The waves arriving at the mobile and their reflections are traced out by considering the intersection of vectors with sides of the rectangles. In the case of the primary waves, the vector joins the mobile to the center of the block under consideration. The wave is only valid for the simulation if no other block intervenes between these two as shown in Fig. 2(a). The vector for a reflected wave starts at the primary intersection, with its direction being defined by the angle of the primary wave. A reflection is considered to be valid if it intersects with another rectangle on the plan. The composite signal received at the mobile is calculated by summing all of the waves, at each increment of time, according to (5)–(9). The angles of arrival, and hence the Doppler shifts, are defined by the primary waves, and the initial phases and magnitudes of the waves are assigned for each run by the use of a random-number generator. The received phase is equal to the path length divided by the carrier wavelength and added to the initial phase. For the reflected waves, the total path length is used for this calculation. The area plan for which the computational procedure has so far been described is only defined for small areas with a maximum radius of about 250 m and no direct component. Fortunately, the majority of the scattered waves originate within this area, but there is, at times, a significant proportion of energy which is received, either directly from the transmitter or by reflection from a prominent feature of the terrain. The path length of such a signal is presumed in the simulation to be much longer than the distance traveled by the mobile during a simulation run. With this assumption, which is not unrealistic for the mobile environment, the angle of the signal received directly from the transmitter (or distant large reflector) at the mobile may be considered to be a constant and so constitutes a coherent wave. Coherent waves are easily accommodated within the simulation and have their paths traced in a similar manner to any other wave. As shown in Fig. 2(b), the wave can be received at the mobile either directly or indirectly by a single reflection. The path is traced by computing the possible angles at which the wave could arrive and is considered to exist if it does not cross any other rectangle. The Doppler shift equation, (5), is used to calculate the received phase, because its arrival angle is constant. The amplitude of the wave is assigned at the start of the program and is simply added to the composite signal in the same manner as for other waves.

2) Simulation Programming: The major part of the program is written in Fortran IV although the central section of the program has had to be developed using Assembler language. This measure was found to be necessary since a typical simulation plan involving 50 scatterers would require 100 wave paths to be traced for each time increment of the program. In checking each of these wave paths to ensure that they are not obstructed by any of the rectangles, a possible 14 million checks for a typical run of 3000 time increments is required (corresponding to a time run for a vehicle of 20 s). Clearly, any time saved in performing this routine has a considerable effect on the total run time of the program as a whole. With all the analysis routines included, the program requires a store of over 100 kbytes, much of which is overlaid, and takes about an hour for each run on a time-shared computer. Each of the routines has been individually checked by inputting known data and comparing the output to the results calculated by hand. Using these results, much of the data has been rearranged in order to permit sequential accessing and, hence, faster addressing modes.

The data input to the program not only defines the plan but also provides other parameters, such as transmitter frequency, transmitter power, mobile speed, run duration, and two random numbers. These two random numbers are used as seed numbers for the random-number generators to assign each of the rectangles with their respective amplitudes and phases. Great care was taken to ensure that the generators produced a flat probability distribution between 0 and 1, and that even the smallest possible change in seed numbers produced a completely new set of random numbers to be generated. The phases are assigned to each rectangle after changing the bounds of the random number generated to 0–2π radians. The phases are then uniformly distributed in a unit circle. Without further information to the contrary, this would seem to be a reasonable choice. The amplitudes, however, are chosen to have a narrow Gaussian distribution as suggested by Gilbert [14] which seems more plausible than Clarke's [12] use of equal amplitudes. The distribution has a variance of 0.1 times the value of the mean, the mean itself being defined by the transmitter power, an input parameter to the program.

3) Validation of Simulation: A prerequisite of all simulation work is validation of the predicted results with those obtained by field trial or experiment. However, since multipath fading is inherently a random process, little information can be obtained from a simple visual inspection of the amplitude/time profile, i.e., the measured fading waveform. For this reason, a separate section of the simulation package was written to provide a full statistical analysis of the fading signal in both the time and frequency domains. Each of the statistical functions can be plotted by means of an incremental graph plotter and superimposed on the curves derived from the theoretical model proposed by Clarke. It should be noted that the same statistical package is used for both the simulation and field trial results. Slow variations in the mean level of the signal are removed by means of a running-mean technique similar to that used by French [18] in his UHF propagation measurements in London.

III. Sideband Diversity

Gosling and Petrovic [6] were the first to study sideband diversity and their work was subsequently extended both theoretically and experimentally by Gosling *et al.* [7] and Allen *et al.* [8]. As already indicated, this form of diversity can only be utilized in multiple transmitter schemes, the individual base stations operating quasi-synchronously or synchronously. For the basic system, the sidebands transmitted from each station are the same as in conventional AM transmission although the sidebands can also be amplitude or frequency modulated subcarriers. In each case, the theoretical analysis is similar and only the basic system will be considered here. Since the base station transmitters are spatially separated by a distance of at least several miles for long baseline systems, it is assumed that their fading due to multipath propagation is uncorrelated. The modulation for each base station transmission is shifted in phase with respect to the first transmitter. The received signal is the complex sum of all the individual waves and the quadrature components of the demodulated sidebands are

Upper sideband (USB)

$$T_{cu} = \sum_{n=1}^{N} \{T_{cn}\cos(d_n) - T_{sn}\sin(d_n)\} \tag{12}$$

$$T_{su} = \sum_{n=1}^{N} \{T_{sn}\cos(d_n) + T_{cn}\sin(d_n)\} \tag{13}$$

Lower sideband (LSB)

$$T_{cl} = \sum_{n=1}^{N} \{T_{cn}\cos(d_n) + T_{sn}\sin(d_n)\} \tag{14}$$

$$T_{sl} = \sum_{n=1}^{N} \{T_{sn}\cos(d_n) - T_{cn}\sin(d_n)\} \tag{15}$$

where T_{cn} and T_{sn} are the quadrature components of the received signal for each transmitter and d_n is the phase of the modulation. The complex sidebands are defined as

$$Z_u = T_{cu} - jT_{su} \tag{16}$$

$$Z_l = T_{cl} - jT_{sl} \tag{17}$$

and their magnitudes

$$r_u = |Z_u| = \left(T_{cu}^2 + T_{su}^2\right)^{1/2} \tag{18}$$

$$r_l = |Z_l| = \left(T_{cl}^2 + T_{sl}^2\right)^{1/2}. \tag{19}$$

If the multipath fading of each transmitted signal is assumed to fit the "Rayleigh" model, then T_{cn} and T_{sn} are normal uncorrelated random variables with zero mean and equal variance, for any individual transmitter. By the central limit theorem [19], T_{cu}, T_{su}, T_{cl}, and T_{sl} are also normal random variables with zero means and equal variances.

The only improvement in quality for either of the sidebands, with respect to a single transmitter scheme, is due to the increased mean power level. However, if the magnitudes of the sidebands are uncorrelated, the final output of the receiver can be derived by selection or combination to produce a signal which experiences less variation in level. When the sidebands are statistically independent, then the joint density function is equivalent to the product of the individual density functions and the distribution for the selected signal can be shown to be

$$F(r_s < R) = \left(1 - \exp\left(\frac{-R^2}{2\sigma_T^2}\right)\right)^2 \tag{20}$$

where the variance σ_T^2 is the same for each sideband and equal to the sum of the individual variances. It is relevant to note here that it is not the authors' intention to present detailed statistical analysis of sideband diversity, since the theoretical basis of selection diversity and the effect of envelope correlation are well documented in the literature.

The distribution function defined by (20) is shown in Fig. 3 and shows the maximum degree of improvement obtainable with this form of two-branch diversity. Unfortunately, the sidebands are, in general, partially correlated and this leads to a partial degradation in system performance [20]. This degradation is also shown in Fig. 3 where the theoretical variation in system performance with correlation coefficient has been computed. It is noteworthy that even with a correlation coefficient for the envelopes, ρ_r, as high as 0.3, there is a 7 dB improvement at the 0.99 probability level.

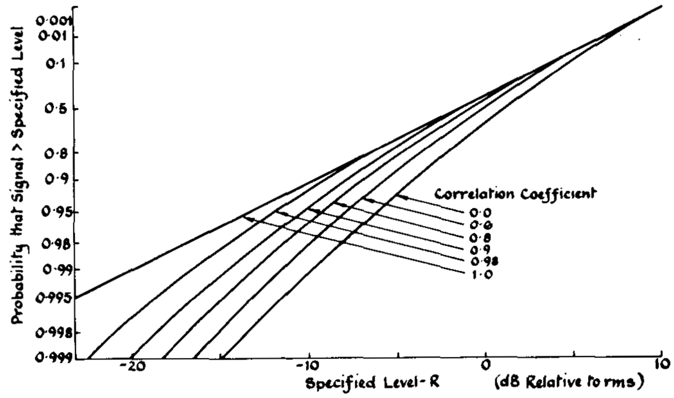


Fig. 3. Distributions for the diversity scheme.

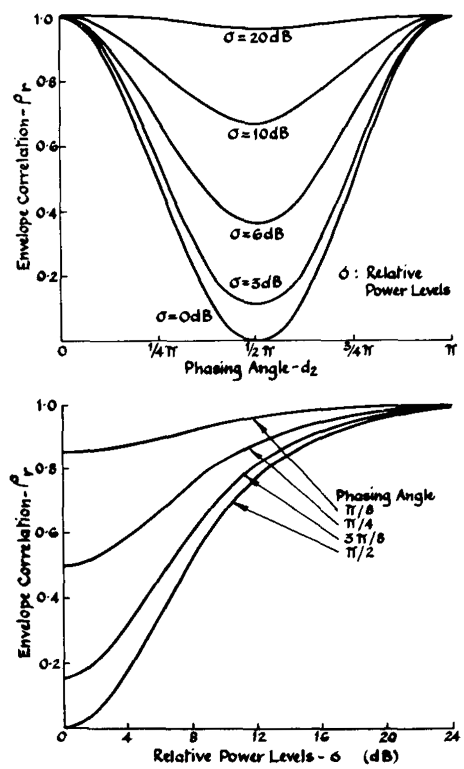


Fig. 4. Correlations for two-station scheme.

A. Two-Station Diversity Scheme

Since the majority of the simulation and field trial work to be described relates to the two-station diversity scheme, it is helpful at this point to review in graphical form some of the more significant characteristics of such systems.

Using one transmitter as a reference, it is possible to show [20], [21] that the minimum correlation occurs when the modulation phase d_2 of the second transmitter with respect to the first is $(2n-1)\pi/2$ and, similarly, when the variances of the two signals are equal. The variation of correlation coefficient with mean power level and phasing angle is shown in Fig. 4.

For the limiting case of $d_2 = \pi/2$, the sidebands can be derived from (12)–(17) as

$$\begin{aligned} Z_u &= (T_{c1} - T_{s2}) - j(T_{s1} + T_{c2}) \\ Z_1 &= (T_{c1} + T_{s2}) - j(T_{s1} - T_{c2}) \end{aligned} \tag{21}$$

or in polar form as

$$\begin{aligned} Z_u &= r_1\cos\theta_1 - r_2\sin\theta_2 \\ &\quad - j(r_1\sin\theta_1 + r_2\cos\theta_2) \\ Z_l &= r_1\cos\theta_1 + r_2\sin\theta_2 \\ &\quad - j(r_1\sin\theta_1 - r_2\cos\theta_2). \end{aligned} \tag{22}$$

The magnitudes are given by

$$\begin{aligned} r_u &= \left(r_1^2 + r_2^2 + 2r_1r_2\sin\theta_d\right)^{1/2} \\ r_l &= \left(r_1^2 + r_2^2 - 2r_1r_2\sin\theta_d\right)^{1/2}. \end{aligned} \tag{23}$$

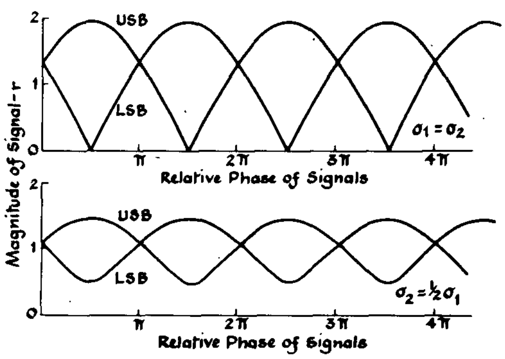


Fig. 5. Sidebands for quasi-synchronous system.

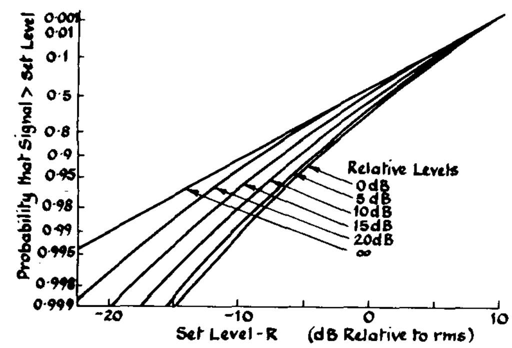


Fig. 6. Distributions for two-station scheme.

In a synchronous sideband diversity system, the phase angle θ_d represents the difference between the random phase shifts of the two signals, whereas in a quasi-synchronous system, this phase angle also includes the shift due to the offset in carrier frequency, ω_q, between the base stations:

$$\theta_d = \theta_1 - \theta_2 + \omega_q t. \tag{24}$$

If the mobile is stationary, then the magnitudes and phases of the received signals are constant over short intervals of time. However, the amplitudes of the envelopes vary with time due to the frequency offset between the transmitters, and two examples of this situation are shown in Fig. 5. If the output of the receiver is derived by selecting the larger of the sidebands, then its amplitude is given by

$$r_s' = \left(r_1^2 + r_2^2 + 2r_1r_2\sin\theta_d\right)^{1/2} \qquad \text{for } 0 < \theta_d < \pi. \tag{25}$$

The minimum value of this signal is $(r_1^2 + r_2^2)^{1/2}$ and it can increase by a further 3 dB. The mean square level of the selected signal is

$$\begin{aligned} E(r_s^2) &= E(r_1^2) + E(r_2^2) + 2(E(r_1)E(r_2)E(\sin\theta_d)) \\ &= \sigma_1^2 + \sigma_2^2 + 2\sigma_1\left(\frac{\pi}{2}\right)^{1/2}\sigma_2\left(\frac{\pi}{2}\right)^{1/2}\frac{1}{\pi} \\ &= \sigma_1^2 + \sigma_2^2 + \sigma_1\sigma_2. \end{aligned} \tag{26}$$

If the variances are equal for each signal, then

$$\sigma_s^2 = 3\sigma^2 = 1.5\,\sigma_T^2. \tag{27}$$

Furthermore, (26) can be arranged in terms of the correlation coefficient as

$$\sigma_s^2 = \sigma_T^2\left(1 + \frac{1}{2}(1-\rho_r)^{1/2}\right). \tag{28}$$

This expression agrees with that obtained by Downton [22] in his parallel work on reliability theory. It implies that the maximum mean square level of the selected signal is 1.5 times the variance of each sideband. As the mean level of one station decreases relative to the other, the variance of the selected signal tends to that for one sideband. If only one station is significant, then, as might be expected, the mean power level drops to the level of that station. The correlation of the sidebands becomes unity and there is no longer any benefit to be derived from the sideband diversity scheme. This situation is illustrated in Fig. 6 where the distribution function has been replotted for the two-station scheme in terms of the relative power levels as opposed to correlation coefficient.

IV. Digital Simulation and Field Trials for Sideband Diversity

A. Simulation

The sideband diversity scheme requires that two major modifications be made to the simulation program described earlier. The first of these changes enables the inclusion of more than one transmitter and the second involves the incorporation of the sideband selection processes. The environmental plan is common to all the signals received by the mobile. Since the fading for each of the transmissions should be independent, the magnitudes and phases assigned to the blocks are unique for each station. The transmitters can also contribute separate coherent waves as required. The wave tracing need only be performed once per increment of time since the positions of the blocks are common for all the signals. The resultant received signal is calculated for each transmission separately. The frequency offsets in a quasi-synchronous scheme are included as modifications to the phases of the waves.

The complex sidebands of the composite received signal are calculated using (12)–(17). The phase shifts d_n for the modulation are set by default as

$$d_n = \frac{(n-1)}{N}\pi \tag{29}$$

for a scheme involving N stations. Allen [21] has shown that equal spaced phasing produces the lowest correlation between sidebands. These phases can also be specified as part of the input to the program. The final output from the receiver is obtained by selecting the larger, in amplitude, of the two sidebands. A record is also maintained of the instantaneous phase of the output signal. The program also has the facility to compute the mean and variance for both sidebands and the selected signal from which, using the covariance of the sidebands, the correlation coefficient may also be calculated.

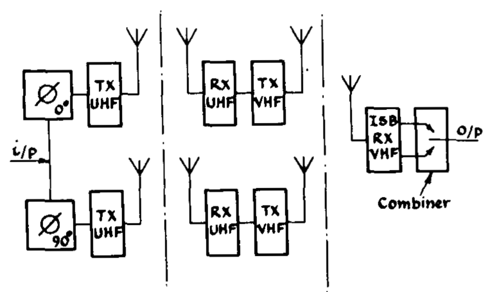


Fig. 7. Two-station diversity scheme.

B. Field Trials

To verify the theory and simulation techniques described so far, a series of basic field trial measurements with a two-station quasi-synchronous sideband diversity scheme were undertaken. Although, in principle, these trials were very similar to those for the single transmitter system, described by the authors in a previous publication [5], the construction and calibration of the multitransmitter scheme was very much more complex and time consuming, and soon proved the vast potential benefits to be gained from using simulation techniques in communication systems design.

In order to satisfy the requirement that the fading for each received signal should be independent, it is necessary to operate the base station transmitters at different sites. Although it was not possible to operate the transmitters on a long baseline system, i.e., the distance between transmitters is of the same order as the distance from base station to mobile, it was feasible to operate a short baseline system within the confines of the University of Bath and still ensure that the transitted signals arrive at the mobile antenna with extremely low correlation of fading statistics. It is usually accepted that a separation of at least 10 wavelengths is required for this purpose. In the quasi-synchronous scheme constructed at Bath, one remote station was situated on top of the Wessex House high-rise block (215 m above sea level) and the other co-sited with the base control in the School of Electrical Engineering (200 m above sea level). A schematic diagram of the two-station diversity schemes investigated is shown in Fig. 7.

The modulation phasing for the transmissions has to be carefully monitored. In order to ensure that no errors are introduced by the equipment, both remote stations are controlled, as they would normally be in practice, by the use of FM link radios. Since the FM sites are similar, and the link paths are not excessively long, the modulation phase shift introduced by each is approximately the same. The actual phasing between the modulations is achieved by using two all-pass filters which, in our case, have a phase difference of $\pi/2$ between them over a frequency range of 300 Hz–3 kHz. Each of the transmitters in the Pye U450L UHF FM link equipment could be keyed separately to control the two remote stations. The nominal power of the transmitters was 6 W at carrier frequencies of 461.750 and 467.450 MHz using 12 element Yagi aerials.

In the remote stations, the link receiver is connected via buffer amplifiers to Pye M201 VHF AM transceivers operating at 86.2875 MHz. The squelch relay in the UHF set controls the power supply to the VHF set. In order to enable the two transmitters to operate quasi-synchronously and to allow the carriers to be set within 1 Hz of each other, it was found necessary to achieve a stability of $1:10^8$ and, therefore, to derive the carrier frequencies from suitable phase-locked synthesizers. The output power of the VHF sets is nominally 6 W and, in our trials, a single 1 kHz sinusoidal tone at 50 percent modulation depth was used for convenience.

In respect of the mobile receiver, a Pye W20 VHF transceiver, a major modification has occurred in that the sidebands are now independently demodulated at 455 kHz before being logarithmically compressed and recorded. Since the accuracy of the IF carrier frequency into the independent sideband (ISB) receiver is fairly critical, it has meant replacing the test receivers first local oscillator with a temperature compensated crystal oscillator (TCXO) in order to achieve the necessary stability. A block diagram of the ISB receiver is shown in Fig. 8(a). The frequency response of the receiver, Fig. 8(b), shows an unwanted sideband suppression of at least 45 dB over the full audio bandwidth. Each of the independent sideband outputs is then fed to an audio frequency logarithmic amplifier which has a dynamic range in excess of 80 dB. The circuit, which is based upon the Texas Instruments TL441, is shown in Fig. 8(c) and feeds a four-track instrumentation tape recorder (Tandberg TIR 115D).

C. Data Processing

In validating the theory and simulation package described thus far, it is imperative that the complete receiver system, including logarithmic amplifier and tape recording system, be so characterized that on playback in the laboratory the field strength can be accurately computed. For this reason, a set of automatic test programs have been written for a PDP8/e minicomputer which 1) enable the characteristic curves for the combined receiver/tape recorder system (i.e., the signal strength/tape recorded voltage curves) to be quickly and accurately computed over the signal range -60 to -130 dBV in 1 dB steps, and 2) allow the recorded signal voltage to be sampled after a run and converted to field strength via the characteristic curves for each channel. The field strength data are now correctly formatted in the minicomputer for further processing. One such program written allows either sideband to be outputted or permits the selection of the larger of the two sidebands at any instant of time. Full analysis of the trial data is performed by transforming the data output file over a high-speed link to the University mainframe computer where it is submitted as the input to the main simulation package (QUASIM). In connection with the automatic test routine described in 1) above, it should be noted that the ISB receiver/tape recorder system was characterized both im-

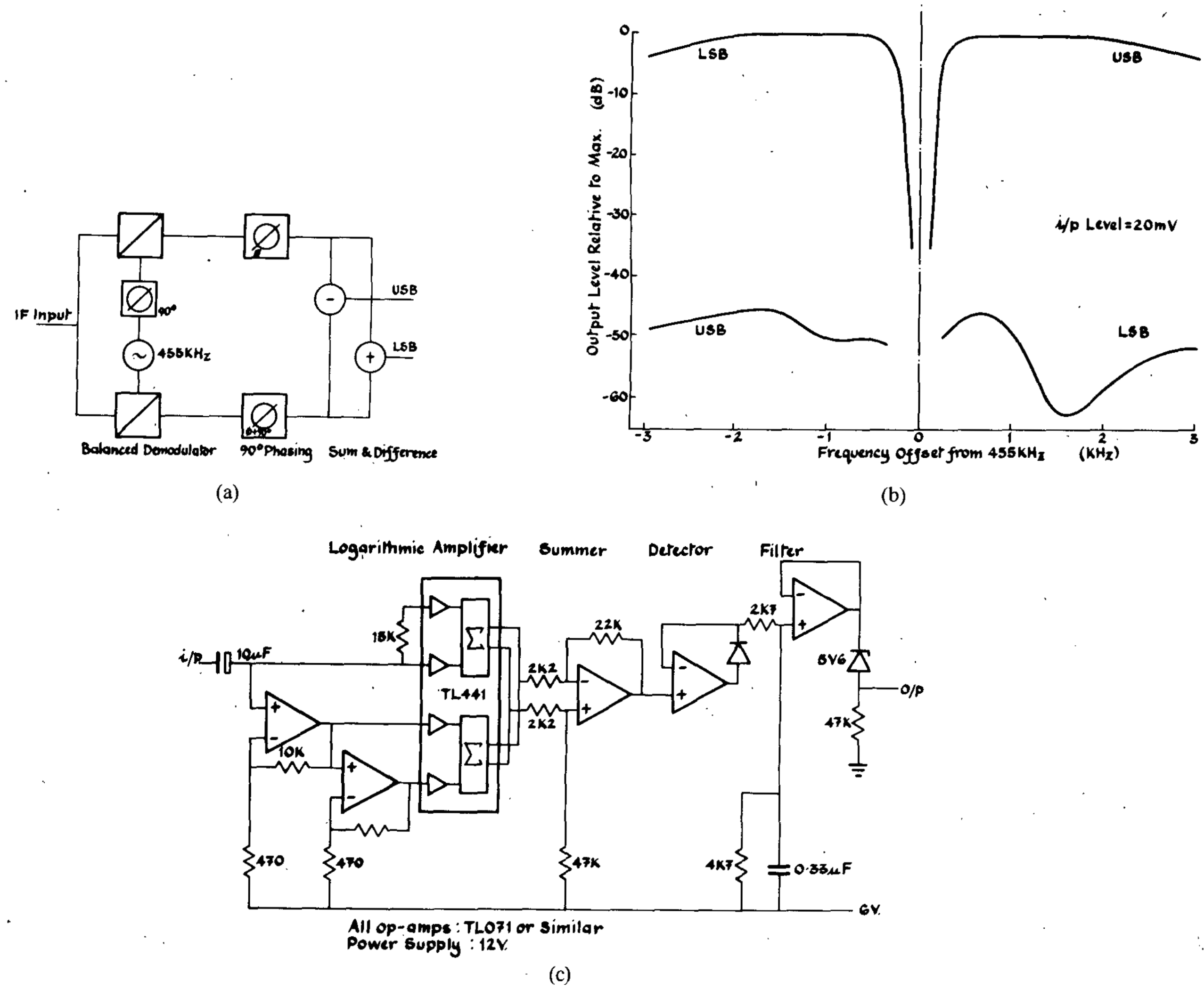


Fig. 8. (a) ISB receiver block diagram. (b) ISB receiver frequency response. (c) Circuit for logarithmic amplifier.

mediately before and immediately after a field test to ensure that the characteristic curves had not changed. Tests in the laboratory showed no perceptible change in characteristics over normal operating times and temperatures. Finally, a program was available in the PDP8/e which computed the means, variances, and correlation coefficient for the two sidebands. These values can be compared with both theoretical and simulated results. In order to draw meaningful conclusions they must also be related to the relative transmitter.

V. Experimental and Simulator Results

A. Validation

In order to check the validity of the basic simulation package for the sideband diversity scheme, a series of field trials were conducted in the City of Bath. The single transmitter tests performed by the authors demonstrated that Great Pulteney Street and its simulation plan both have fading statistics which approximate very closely to the "Rayleigh" model, Fig. 9. Since Rayleigh statistics are the preferred norm in mobile radio investigations, this particular road in Bath was used to obtain the results for the diversity scheme. Before doing so, however, trials were conducted using each of the remote stations separately. In verifying that the fading statistics for each of the transmitters obeyed Rayleigh statistics, it was noted that the mean level of the signal from the Wessex House site was some 20 dB higher than that positioned at the School of Electrical Engineering. Unfortunately, it was not possible to set the powers closer than 10 dB apart without incurring instability problems. No variation in their levels was detected during experimental runs and no correlation was found between the signals from the two stations. The offset between the carrier frequencies was almost 1.0 Hz and this figure was used for the input to the simulation. The area plan for Pulteney Street shown in Fig. 9 was used in the simulation with the addition of a transmitter whose power was set at -10 dB. The results obtained from the simulation and experimental investigations are shown in Fig. 10. The time profile and the cumulative distribution both clearly show the benefit to be obtained from the sideband

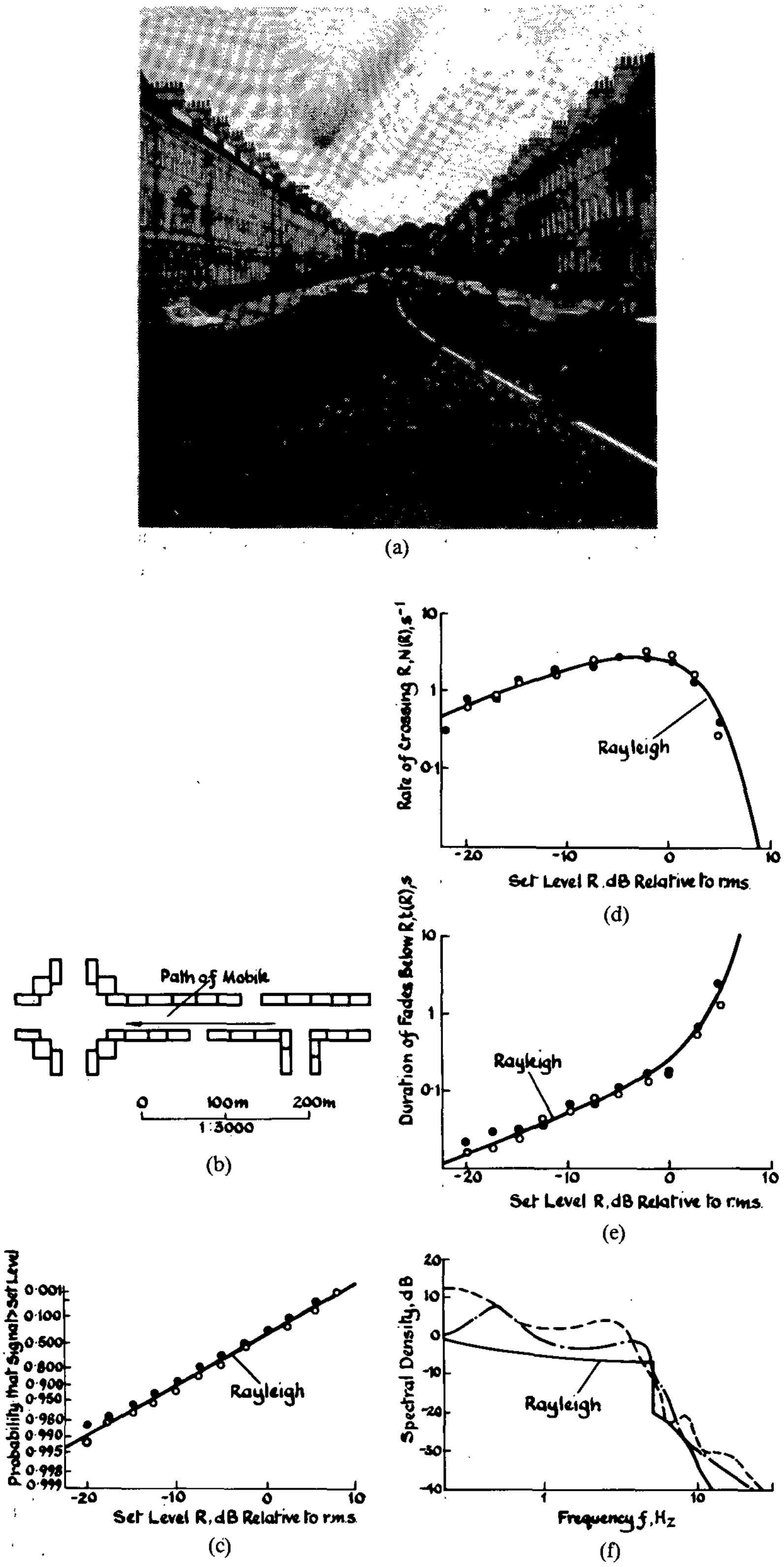
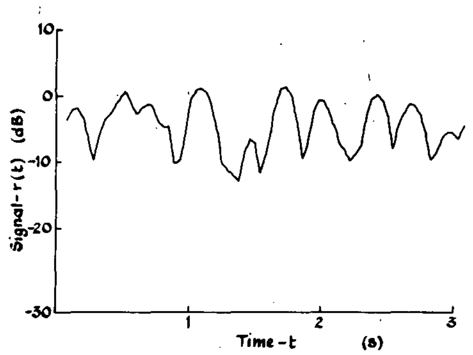
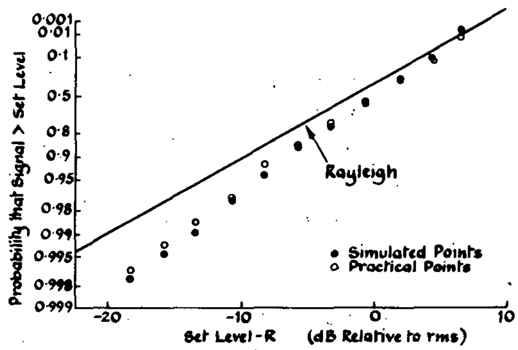


Fig. 9. Great Pulteney Street, Bath, England. (a) View of street. (b) Computer simulation plan. (c) Comparison of simulated, experimental, and theoretical Rayleigh cumulative distribution functions. (d) Comparison of simulated, experimental, and theoretical Rayleigh level crossing rates. (e) Comparison of simulated, experimental, and theoretical Rayleigh mean duration of fade. ● simulated points; ○ experimental points. (f) Comparison of simulated, experimental, and theoretical Rayleigh power spectral density curves. — - — - simulated curve; - - - - - - experimental curve.



(a)



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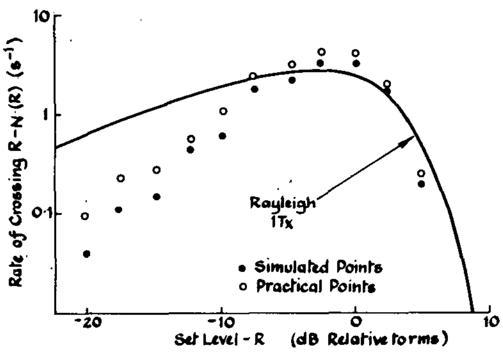

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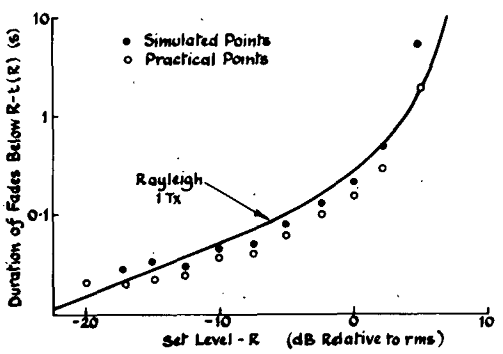
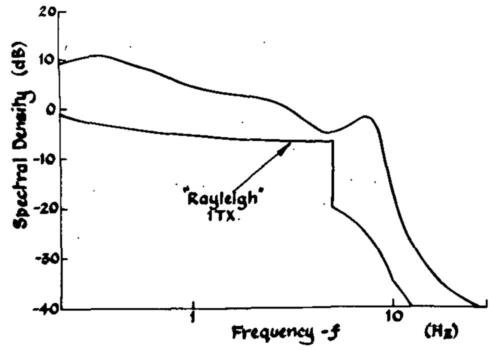
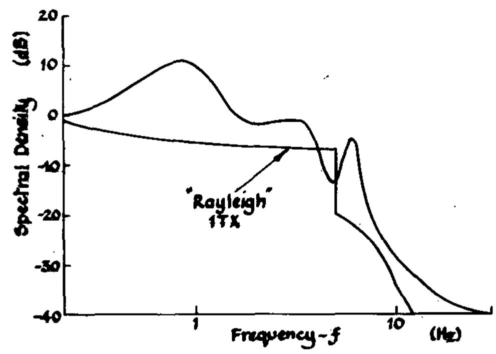


(d)

Fig. 10. Statistics for the diversity scheme. (a) Simulated time profile. (b) Cumulative distributions. (c) Level crossing rate. (d) Mean duration of fades.



(e)



(f)

Fig. 10. (*Continued*) (e) Practical power density spectrum. (f) Simulated power density spectrum.

diversity scheme even with the relative power difference used. These statistics will be discussed more fully in the next sections, it is sufficient here to note the similarity between the practical and simulated statistics.

B. Synchronous Sideband Diversity Scheme

The confidence gained from the results in the previous section permits us to extend the simulation runs to differing operations conditions to try to gain a clearer understanding of the sideband diversity scheme. The results described in this section relate to the synchronous scheme since they can be compared directly with the theory given previously. All runs use the area plan for Great Pulteney Street.

The first series of computational tests employed one-, two-, and three-transmitter schemes, the single transmitter test acting as a benchmark. For the two- and three-transmitter schemes it was initially assumed that transmitters have equal power levels. The cumulative distribution function for the envelope of the selected signal, shown in Fig. 11, clearly shows the predicted improvement for the two-transmitter scheme in overcoming the effects of multipath propagation. The addition of a third transmitter has no significant effect on the multipath fading, although it does increase the mean power level by 2 dB. The similarity between the statistics of the two- and three-transmitter schemes is also apparent from the crossing rate and fade

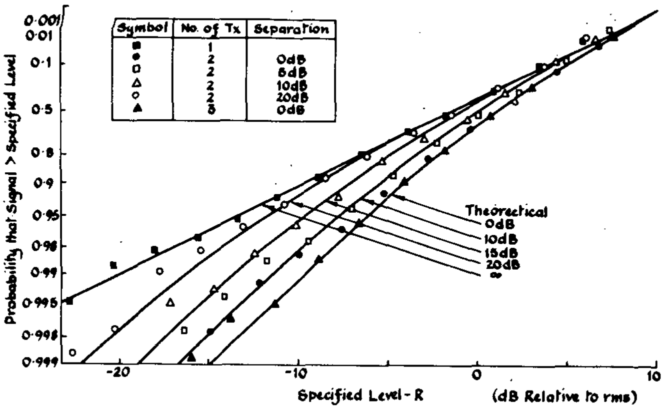


Fig. 11. Simulated cumulative distributions.

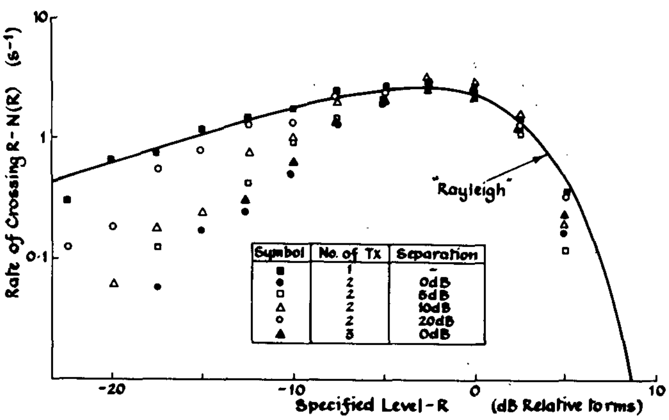


Fig. 12. Simulated crossing rates.

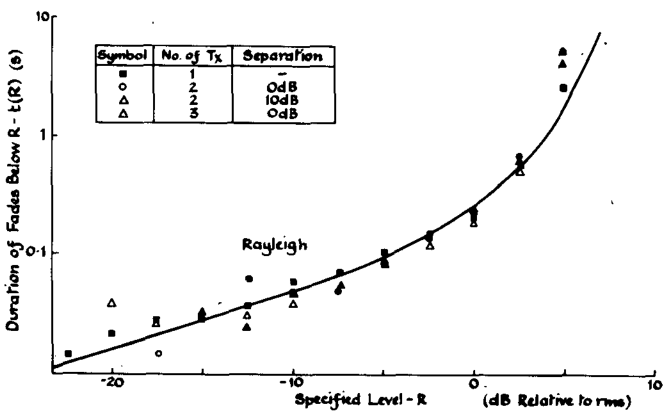


Fig. 13. Simulated fade durations.

duration curves shown in Figs. 12 and 13. This result is not entirely unexpected since the main diversity occurs between the sidebands, of which there are, of course, only two. The addition of the third transmitter will, however, substantially improve the area coverage by substantially reducing the number of signal "black spots." From the crossing rate curve it is evident with the multitransmitter schemes that the signal does not cross the lower levels as often as with the single transmitter scheme. When the

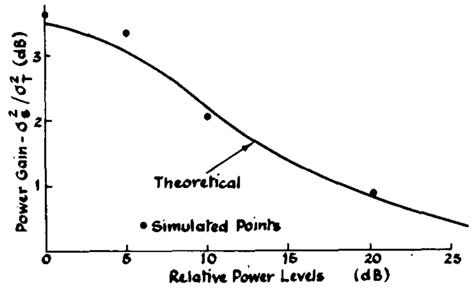


Fig. 14. Power gain for diversity.

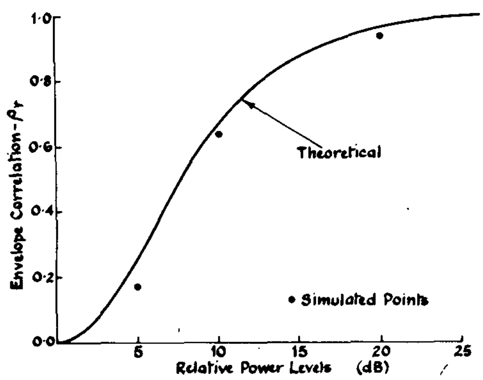


Fig. 15. Correlation coefficient for the diversity scheme with relative power levels of transmitters.

signal does cross these levels, however, it stays below them for approximately the same period of time (Fig. 13).

In a second series of computational tests for the synchronous system, a two-transmitter scheme with a range of relative power levels between them was investigated. From the cumulative distribution plots shown in Fig. 11, it would appear that the fading for the simulated signals is slightly worse than predicted by theory. However, the simulated points still follow the general trend of the theoretical curves. As the difference in the power levels increases, so the crossing rate gradually moves towards the curve for the "Rayleigh" model. The fade duration curves show no significant deviation from the single transmitter scheme.

Another test of accuracy for the simulation package is to compare the computed power gain, due to the selection of the signal, and the correlation of the two sidebands with those values predicted theoretically. The phasing of the modulation is held constant at 90° for all of these tests. The results are plotted in Figs. 14 and 15 and a very close correspondence between theory and simulation is observed. The power gain is expressed in terms of the total power in either of the sidebands, that is, the power level that would be received if there was no selection.

C. *Quasi-Synchronous Sideband Scheme*

In a quasi-synchronous scheme the individual signals beat together at a rate proportional to the offset between the carrier frequencies. Sideband diversity overcomes this extra signal fluctuation by always selecting the larger of the

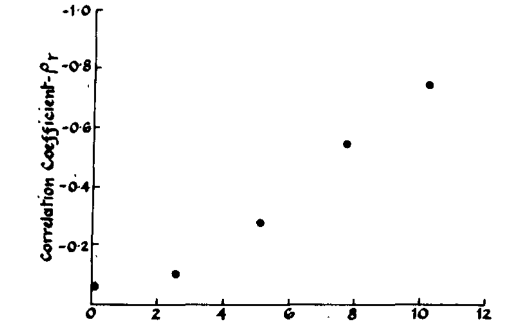


Fig. 16. Correlation coefficient for the diversity scheme with carrier offset between the transmitters.

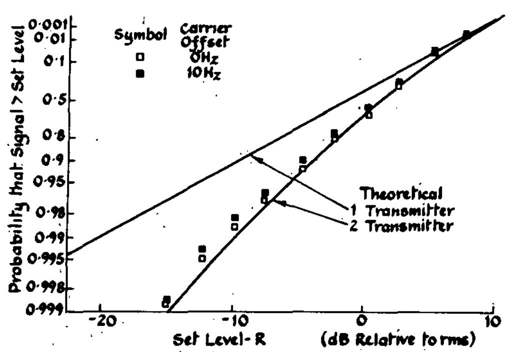


Fig. 17. Distributions for increasing frequency offset between transmitters.

sidebands. When the receiver is stationary, then the incoming signals experience beats at different times as shown in Fig. 5. With the phasing set at 90° for the two-transmitter scheme, then the correlation of the sidebands approaches -1 as the relative power levels of the signals become equal. When the mobile moves, the signal also undergoes multipath propagation with its consequent fading, and the envelope correlation increases with the mobile speed until it becomes positive again.

No theoretical work has yet succeeded to the authors' knowledge in evaluating the relationship between the maximum Doppler shift of the received signal and the offset in carrier frequency with regard to the correlation of the sideband envelopes. Using the same plan as before, with a two-transmitter scheme and equal power levels, the simulation has been run for a number of different carrier offsets. From the plot (Fig. 16) of the correlation coefficient it can be seen that the offset frequency has a marked effect, the maximum Doppler shift being 2.57 Hz for this run. There is a reasonably small change in the cumulative distribution function (Fig. 17), and there is also some evidence [23] that the offset frequency can decrease the duration of deep fades although it also increases their incidence.

VI. Conclusions

The paper describes the application of a new simulation model for fading in the mobile radio environment to both synchronous and quasi-synchronous full carrier AM sideband diversity schemes. Although the simulation, which takes into account vehicle movement through a given environment, has been successfully applied previously to the case of a single base station transmitter, this is the first application of the simulation package to multitransmitter schemes. From the limited field trials conducted with a quasi-synchronous VHF AM sideband diversity scheme, good agreement has been found between theory, experiment, and simulation. The results presented in the paper show the simulation package to be capable of producing results which are not readily obtainable with conventional simulation techniques. From the simulation it is evident that the diversity scheme can significantly reduce the effects of fading, even when one signal is much smaller than the other. Furthermore, although it has been suggested that no improvement can be expected by the addition of a third transmitter, it must be remembered that information about area coverage has not been included in the paper. Although further work is required to determine the limitations and sensitivity of this digital simulation technique and to provide statistics concerning the phase and random FM of the received signal, the results so far obtained have been extremely encouraging and have indicated its potential in mobile system investigations.

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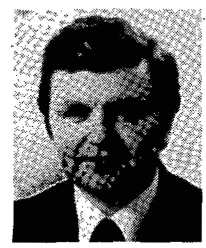

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Queueing Network Simulations of Computer Communication

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***Abstract*—Queueing networks are a powerful abstraction for modeling systems involving contention for resources, e.g., manufacturing lines and computer systems. Queueing networks are especially effective in modeling computer communication systems. Most papers concerning queueing models of communication describe analytic solution of queueing models. This paper describes simulation models based on "extended" queueing networks. The primary advantage of using a queueing network representation for simulation of a computer communication system is the high level of description, in comparison with conventional simulation programming languages.**

For queueing network models to be used effectively for simulation of contention systems, appropriate software is needed. The research queueing package (RESQ) is a general purpose tool for modeling contention for resources and associated system characteristics. RESQ facilitates i) appropriate abstraction of system characteristics through its definitions of extended queueing networks, ii) efficient and convenient definition and revision of models through its integrated interactive and batch model definition interface, and iii) effective experimentation with simulation models through facilities for parameterized sets of experiments, interactive running of simulations and statistical analysis of simulation results. With a tool such as RESQ, an analyst can produce results in days instead of weeks, and so an analyst can answer questions which otherwise would be left unanswered.

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